JOINT HIGHWAY RESEARCH PROGRAM
PROJECT 77-02-3
SEALING CRACKS IN FLEXIBLE PAVEMENTS
INTERIM REPORT II

SCHOOL OF CIVIL ENGINEERING OKLAHOMA STATE UNIVERSITY

RESEARCH REPORT

CRACK DYNAMICS FIELD STUDY

by

Phillip G. Manke
Ismail M. Basha

Publication No. R(S)-19

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and

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RESEARCH PROJECT 77-02-3

Joint Highway Research Program

conducted for the

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CHAPTER I

INTRODUCTION

The first interim report on Project 77-02-3, "Sealing Cracks in Flexible Pavements", was submitted to the Oklahoma Department of Transportation (ODOT) in February, 1977 (1). This report contained a review of literature on the materials and methods of installation used in sealing flexible pavement cracks. The results of an in-state and surrounding state survey to determine currently used sealing materials and installation procedures and the effectiveness of this type of pavement maintenance were included. The report also suggested a three phase research approach directed to: 1) evaluating and/or developing laboratory test procedures that could be used to predict the field performance of sealant materials; 2) carrying out a field study of crack dynamics and; 3) conducting a field test program to evaluate the effectiveness of various application procedures and sealing materials.

The project received additional funding and the second phase of the proposed research, the crack dynamics study, was started in March, 1977. This was a field study of transverse crack movements and behavior under varying conditions of load and temperatures. The purpose of the study was to obtain measurements of the relative horizontal and vertical movements of adjacent pavement sections at transverse cracks in the roadway surface. Such data were considered necessary in order to establish reasonable performance criteria for sealants based on average Oklahoma conditions.

The study was limited to transverse type cracks, since the relative movements of the adjacent pavement sections were expected to be greater than for other types of cracks. Measurements of the width of crack opening and the ambient temperatures at these sites were made at monthly intervals over a period of one year. Vertical deflections at the selected cracks under an 18,000 lb (8,165 kg) axle load were measured at three month intervals during the same period.

The influence of certain environmental factors (pavement temperature, geologic type of subgrade material, and spacing of adjacent cracks) on the relative horizontal and vertical movements at these test site cracks was determined.

CHAPTER II

EXPERIMENTAL DESIGN

An experiment is a planned inquiry to obtain new facts or to confirm or deny the results of previous experiments (2). The design of an experiment is the complete sequence of steps taken ahead to time to insure that the appropriate data will be obtained in a way which permits an objective analysis leading to valid inferences. The crack dynamics field study was set up as a statistically designed experiment to obtain and analyze data on the relative horizontal and vertical displacements of the pavement surface adjacent to full width transverse cracks.

As previously discussed, test sites were established on transversely cracked state highway sections in the central, north-central and northeast areas of the state. Selected transverse cracks at each test site were monitored for their horizontal movements with varying temperature and for their vertical displacements under a specified loading condition.

The Research and Development Division of the Oklahoma Department of Transportation (ODOT) asked specifically that the study include cracks located on certain geological formations of interest. This along with some limitation on travel distance aided in the search for suitable test site locations on the state highway system.

Various highway sections exhibiting different degrees of transverse cracking in a number of maintenance division areas were visited. Some of these sections were suggested by the maintenance engineers and others were located by research personnel during field trips to different locations in Oklahoma for another research program. Preliminary site visits for these locations were made to: 1) locate the cracks and determine their suitability for the intended study, and 2) check the geometric alignment and adequacy of shoulder parking at the prospective sections. This latter aspect was given great consideration to assure that the safety of research personnel could be maintained during future field operations. The final selection of suitable test sites was based on the results of this initial survey and the planned time schedule. The selected sites were situated so that data could be collected at several sections during a single trip. Each of these sites was identified for the respective Maintenance Division so that sealing or overlaying operations would not be carried out at these locations during the study period.

Identification of the test sites was made by attaching a 10.0 in. 11.0 in. (254 mm x 279 mm) red painted metal plate to the right-of-way fence at each test site. These markers were located at a measured odometer distance from the nearest intersection, bridge or the boundary line of the county in which the test sites were located. At each test site, a 0.25 mile (0.40 km) length of pavement was chosen for detailed crack surveying and measurement of the crack spacing. To keep the amount of experimental work within practical research capabilities, a total of nine test sites was finally selected. The selected sites included five sections located on the Wellington-Admire geological unit, two on the Boone unit, and one on both the Senora and the Garber units (3). Table 1 in Appendix A shows the exact locations and the corresponding geological formation unit for these sites.

Horizontal Movement Study

The primary objective of this study was to determine the amount of horizontal movement at transverse cracks during a specified period of time (one year) and relate this movement to seasonal temperature fluctuations and Effective Crack Spacing (ECS). ECS (4) is the average of the distances between adjacent transverse cracks on either side of a crack being studied. It was considered that the pattern of crack movement for various ECS's with respect to temperature variation might lead to a suitable method for predicting horizontal crack movements.

The study started with counting and measuring distances between the cracks within the chosen length of pavement (a Rolatape, Model 200, was used for these measurements). Five cracks were selected at random from among cracks that extended across the full width of pavement. Two steel concrete nails were driven into the bituminous pavement, one on each side of a selected crack. These nails were driven flush with the surface of the pavement to assure no damage from traffic and/or snow removal equipment. A small indentation was placed in the head of each nail to provide reference points for the subsequent measurement of the crack movements.

At the time of their installation, initial measurement of the distance between the two nails was made. This distance was recorded along with the air temperature, the pavement surface temperature and the pavement temperature at a depth of 2.0 in. (51 mm).

At monthly intervals as the temperature fluctuated, the sites were visited and the spacing of the five pairs of nails in each site were measured. Air, surface, and subsurface temperatures were determined at of the opposing pavement edges at a transverse crack and comparing this with the maximum expected horizontal movement. It was hoped that the results would substantiate that the shear strain has a limited effect on the failure of sealants. The seasonal effect on both the total and relative deflection was also investigated.

The method used for measuring vertical crack movements was adopted from the previously cited Virginia study (8). Vertical deflections caused by a truck with an 18,000 lb (8,165 kg) rear axle load were determined using a Benkelman beam. The Research Division of ODOT trained the project personnel in the use of the Benkelman beam and provided the loaded truck for these measurements. They also furnished an experienced man to assist with the beam operation when these measurements were made in the field.

The measurements were made at the same five cracks at each site used in the horizontal movement study. The Benkelman beam was placed on the left side of the loaded truck, which moved in the traffic direction, to make it easier for the driver to locate the rear tire exactly on a painted mark (Figure 1). Hand signals from the measuring crew assisted the driver in positioning the truck. This procedure insured that the load would be applied to the same area each time. Dial readings were taken at three tire positions (Figure 1) with the truck moving forward and, as a check, three more readings with the truck moving backward.

Statistically the experiment can be defined as a "split-plot in time" (2) where crack deflections represented the experimental units. The units secured from each crack (crack No. 1 to crack No. 5) were divided according to their location into eight "main plots", sections 1 through 8. Each main plot was subdivided into four subplots for the winter, spring, summer and fall measurements.

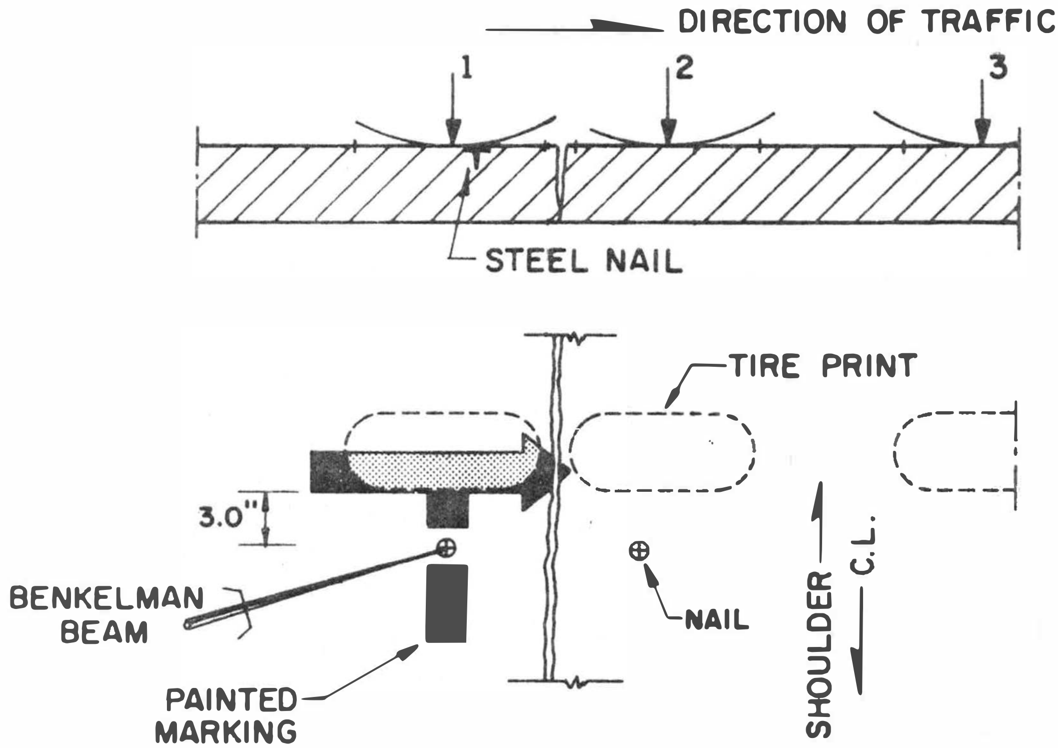


Figure 1. Respective Location of Truck Tires and Benkelman Beam at a Transverse Crack

CHAPTER III

FIELD STUDY PROCEDURES

The field study portion of this investigation was divided into two parts. The first part consisted of measuring the horizontal movement or displacement at transverse cracks due to expansion and contraction of the adjacent pavement sections. The second part of the study involved determination of the relative vertical displacements of the transverse crack sides under application of a heavy wheel load. Knowledge of the magnitude of these respective movements was considered essential to the study and evaluation of crack sealant materials.

Horizontal Movements

Safety

The planning and conduct of all field work on the highways was controlled to a considerable extent by the necessary precautions to insure the safety of the research personnel. Selection of the test sites was based primarily on the availability of adequate sight distance and good shoulder parking conditions for the research vehicle. Field work was not conducted if there was any form of precipitation on the roadway.

No traffic control was provided for the horizontal measurements. The research vehicle, a quarter-ton pickup truck equipped with flashing caution lights, was parked on the shoulder in advance of a test site location to warn oncoming traffic. Research personnel wore high visibility the time of the spacing measurement. The amount of movement, i.e., opening or closing of the crack, was calculated by comparing the initial or original spacing measurement with subsequent ones.

Elements of the statistical design for this study are: 1) Experimental units, includes the geological formation, pavement surface and subsurface types, the average width and degree of cracking and the ECS of a given crack; 2) Treatment, the factor applied to the experimental units or, in this case, the environmental temperature [Note: It is known that the air temperature and the surface and subsurface pavement temperatures are closely related (5) (6), but in this study it was necessary to monitor each to determine which had the greatest influence on crack width]; 3) Response, the amount of movement that takes place at each crack.

A regression analysis method was adopted for analyzing the data of this multivariate experiment, and to develop a mathematical functional relationship between the variables. Some precautions or reservations had to be made in the inference part of the analysis to account for the fact that the ECS element was not chosen at random every time the readings were taken. For practical reasons the ECS was randomly selected initially and then fixed during the remainder of the experiment.

Vertical Movement Study

Based on findings of a Massachusetts study (7), in which shear strain in expansion joints on Portland cement concrete (PC) pavements was found to be relatively small compared with the tensile strain, it was speculated that this might also hold for asphalt pavement cracks. This study was directed toward finding the range of relative vertical displacement safety vests and hats and one man served as a "lookout", observing traffic, while the other man made the necessary measurements.

Initial Installation and Measurements

After selecting a transversely cracked section of pavement for study, measurements of the spacing between full width cracks was made and the ECS(4) was calculated for each crack. Five cracks were randomly selected and their location marked with spray paint on the pavement.

At the selected cracks, steel concrete nails with indentations in the heads were driven into the pavement on each side of the crack approximately 10.0 in. (254 mm) apart. A 24 in. (610 mm) vernier caliper equipped with points to fit the indentations in the nail heads was used to measure the distance between nails (Figure 2). The initial as well as the subsequent monthly measurements were made to the nearest 0.001 in. (0.025 mm).

A 0.25 in. (6.4 mm) diameter hole, 2.0 in. (50.8 mm) deep, was drilled near the edge of the pavement at a location central to the five cracks in a test site. A temperature probe or thermistor was inserted in this hole to obtain the subsurface pavement temperature. A steel bolt and caulking compound were used to seal this hole between the monthly temperature readings. These readings were made using a remote sensing tele-thermometer (YSI Model 47) with separate thermistor probes for gaging the subsurface and surface pavement temperature and the air temperature. Power for the tele-thermometer unit was obtained from a 12 volt battery through a 200 watt inverter.

Monthly Measurements

Each test site was visited once a month over a one year period. The

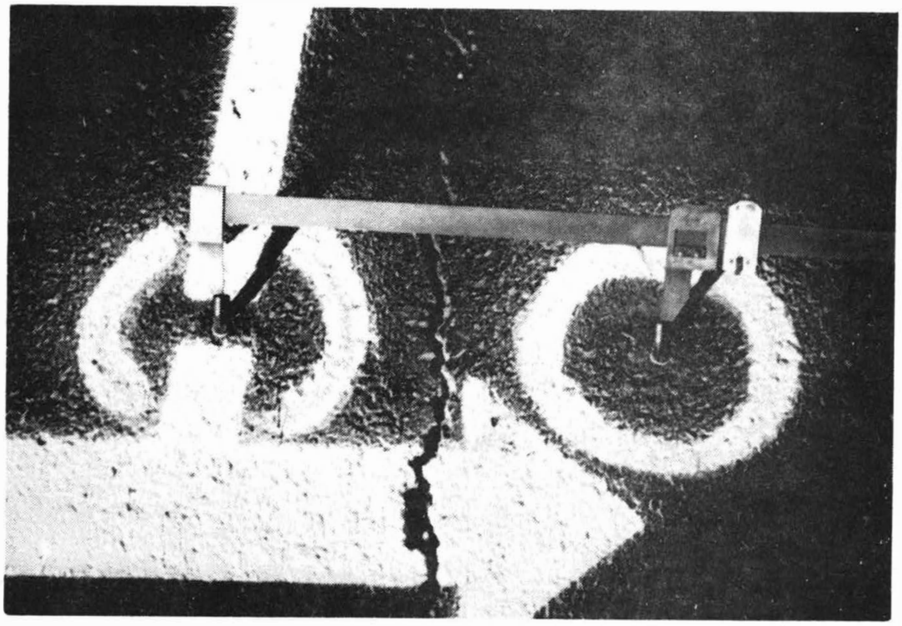


Figure 2. Placement of Reference Nails

test sites were grouped according to their location into three areas. All of the sites in a particular area could be visited, the respective measurements taken and the return trip made within one day. Thus, only three trips per month were required to collect the necessary data from all the test sites.

The nails at the transverse cracks and the temperature probe hole were marked with while painted rings for ease in relocation. After reaching a test site, the truck was parked on the shoulder with lights flashing and the temperature monitoring equipment was set up at the pavement edge (Figure 3). Traffic cones were used to delineate the working area. The subsurface probe was inserted in the prepared hole and the surface probe taped to the pavement surface. The air temperature probe was placed on top of the tele-thermometer unit, approximately 10.0 in. (254 mm) above the pavement surface. The probe temperatures were allowed to stabilize and the readings were recorded.

The distance between the nails at each of the five cracks were then measured with the calipers. Two separate measurements were made at each crack to reduce the chance of error in reading and recording the values. Following these measurements, the various temperatures were again read and recorded to check for variations.

The data collected from each site visit was punched on computer cards using the Statistical Analysis System (SAS) code (9). A card similar to that shown in Figure 4 was made for each transverse crack with the spacing and temperature measurements and other pertinent information punched in the card.

Initial examination of the data obtained after the first few months indicated a need for more information on the affect of crack spacing. Thus, test site No. 9 with a total of 46 cracks was added to the study.

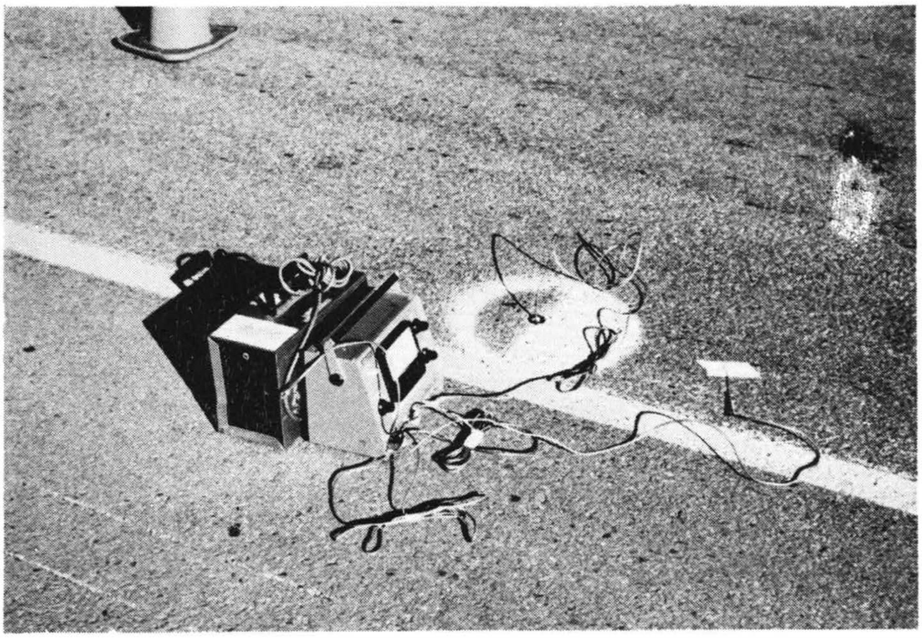


Figure 3. Temperature Monitoring Equipment

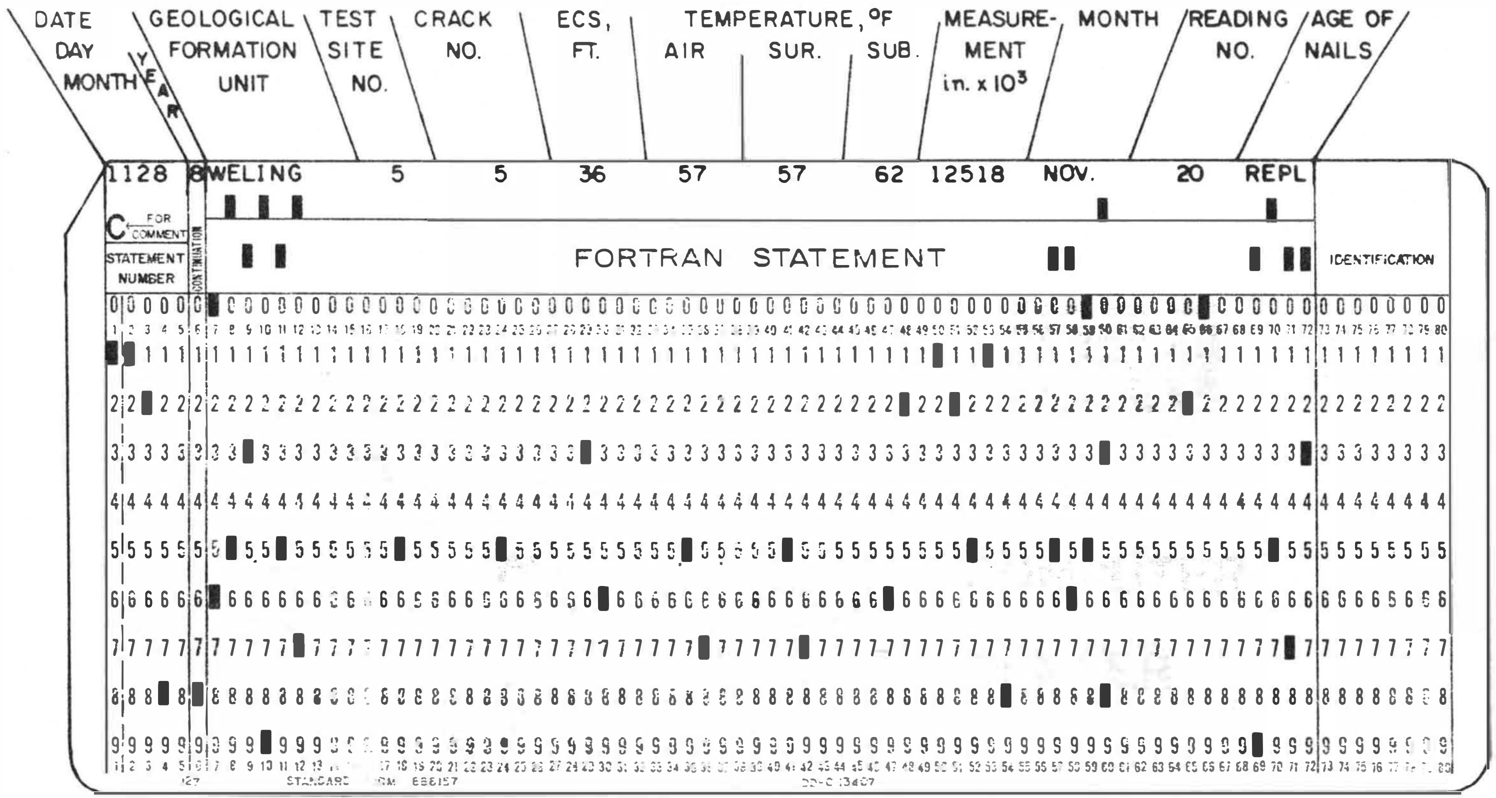


Figure 4. Computer Card with Transverse Crack Data

Lost Nails

A major problem during the one year observation period was the loss of some of the nails or gage points at the cracks. Although the nails were driven flush with the pavement surface, snow removal equipment also removed a few of these nails. The nails at one test site location were covered with an asphalt overlay. As soon as the losses were discovered, the nails were replaced and new initial measurements made but all previous data at these locations were invalidated.

Vertical Deflections

Safety

The vertical deflection measurement procedure required more elaborate safety precautions. One lane of the highway was kept open to traffic while the other was blocked for the measuring operations. At sites with high traffic volumes, appropriate warning signs were placed at least 880 yd (805 m) in advance of the work area. The warning signs were followed by directional markers (traffic cones) and flagmen. The advanced warning signs were not required at test sites with low traffic volumes. After completing the deflection measurements in one lane, the directional markers were switched to permit work in the other lane. All traffic control was handled by ODOT personnel from the Research and Development Division and/or the respective Maintenance Division in which a test site was located.

Site Visit Schedule

Due to the difficulty in arranging cooperative field work as required for the vertical deflection measurements, a different schedule was adopted for these tests. Instead of the monthly schedule used for the horizontal displacement measurements, the vertical deflections at the respective test sites were measured only four times—during the winter, spring, summer and fall seasons of the year. These measuring operations were scheduled in advance with the Research and Development Division. Table II in Appendix A shows a copy of the tentative schedule that was sent to the ODOT. Measurements at the eight sites during a particular season were made within a one week period. This was an attempt to obtain the data under approximately the same environmental conditions at all the test sites.

Deflection Measurements

Having blocked the test lane to all vehicular traffic, the Benkelman beam was placed near the center line of the road with the beam point on top of one of the nails used for the horizontal displacement study (Figure 5). A dump truck loaded to 18,000 lb (8,165 kg) on its rear axle was positioned with its left rear dual tire about 3.0 in. (76 mm) from the beam point (Figure 6). The dial indicator on the beam was set to zero, as the initial beam reading (point 1 in Figure 7a). The first set of measurements was taken with the truck moving in the traffic direction. As the truck was driven slowly across the crack, readings were taken as it reached points 2 and 3. After the reading with the truck tire at point 3 was recorded, the dial indicator was again set to zero and a second set of readings were taken with the truck moving backward to check the initial set of readings (Figure 7b).

The "B" and "D" readings indicate the total amount of deflection of

Figure 5. Starting Position For Deflection Measurements

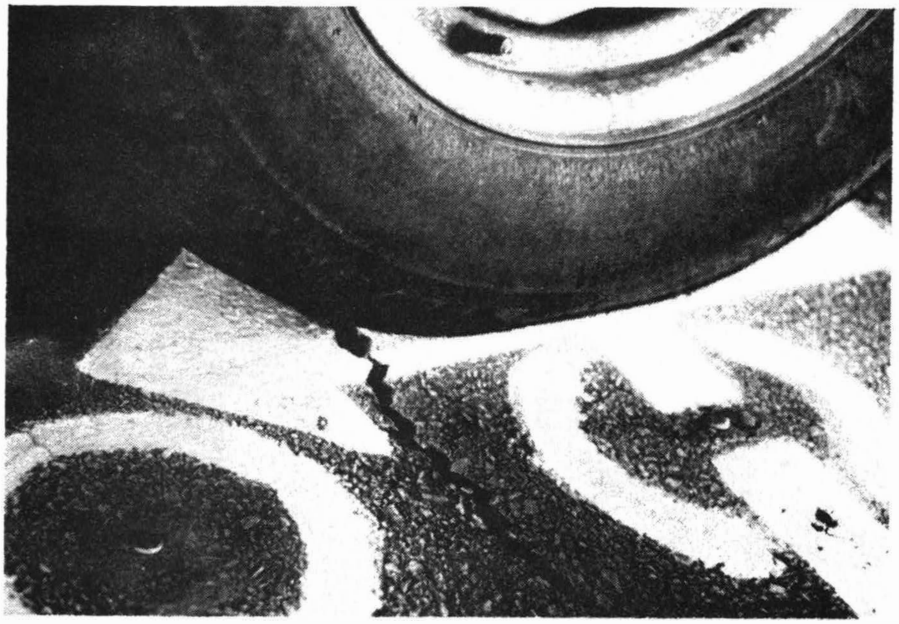
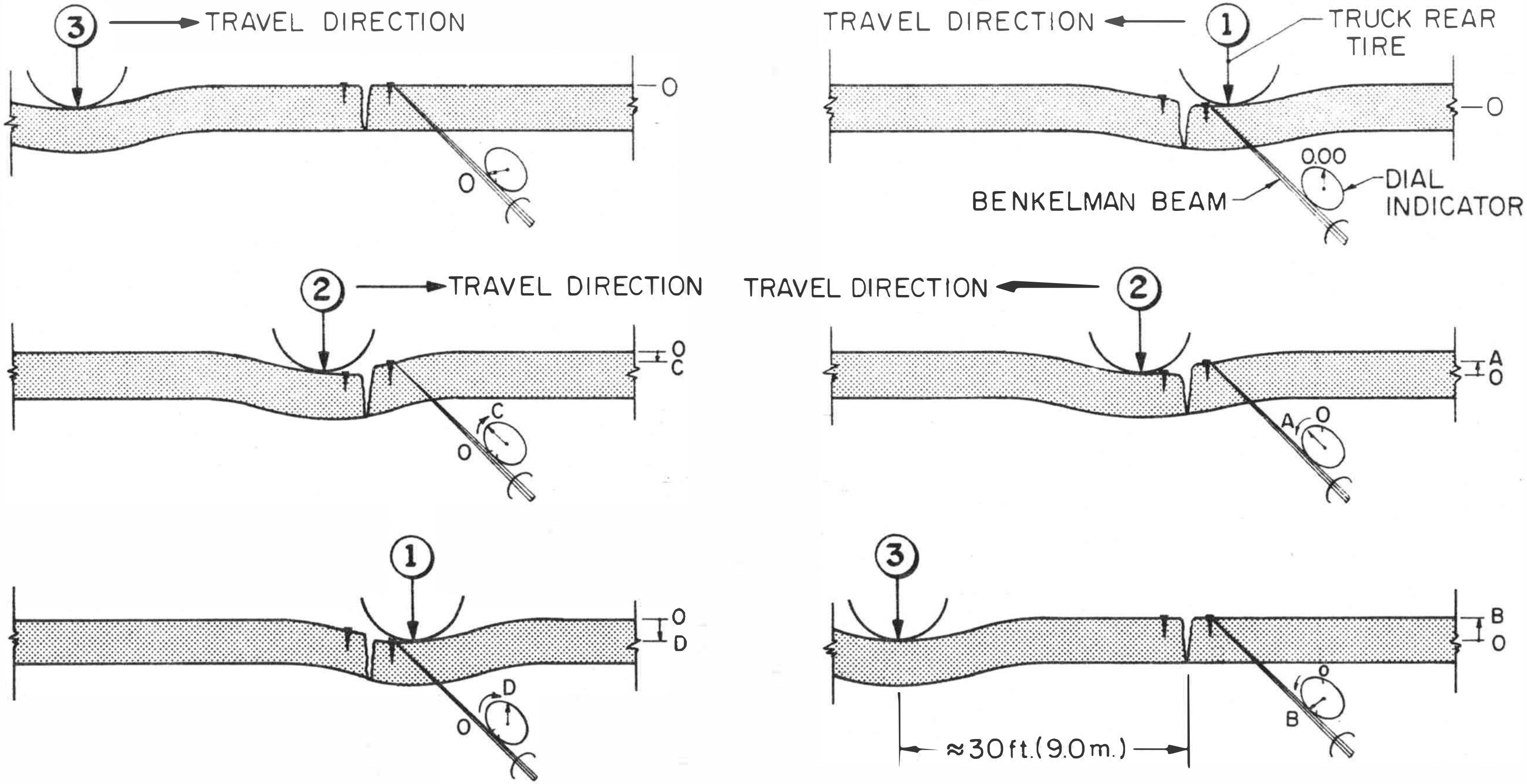


Figure 6. Tire Position for Vertical Movement Measurement



b - TRUCK MOVING BACKWARD

a - TRUCK MOVING FORWARD

Figure 7. Schematic Showing Deflection Testing Procedure

the pavement on one side of the crack under the loaded truck. The dial reading with the truck tire at point 2 is a measure of the amount of relative deflection between the crack sides as the load moves from one side of the crack to the other. The relative deflection was obtained using an expression that averages three different measurements. From Figure 7, the total and relative deflections can be expressed as:

$$\text{Total Deflection, } (T) = \frac{B+D}{2}$$

$$\text{Relative Deflection, } (R) = 1/4\left[\left(\frac{B+D}{2} - C\right)+(D-C)+2A\right]$$

Deflection measurements were made at each of the five cracks at a test site. Temperature readings were also observed at the time of the deflection measurements in order to compare them with average temperatures from climatic records for a particular season of the year.

Deflection measurements with a Benkelman beam are normally made with the beam positioned between the dual tires of a loaded truck (Figure 8). To facilitate measurements during backward motion of the truck, the beam was placed to the side of the dual tires rather than in the usual position. A preliminary study at test site No. 3 indicated a negligible difference in readings with the beam placed between the dual tires and those with the beam placed to the side of the tires. This latter technique simplified the measurement procedure and required considerably less time to obtain the data.

Figure 8. Deflection Measurements with the Benkelman Beam Positioned Normally

CHAPTER IV

RESULTS AND DISCUSSION

Horizontal Movement

The measurements of horizontal movement at transverse cracks were used as input data for a statistical regression analysis. The Statistical Analysis Systems (SAS) computer program (9) was used to develop several mathematical functional relationships between the horizontal movement and the influencing variables. The following model form was used to study the general effect of the temperature and ECS factors on crack movement:

$$Y = f(T,\ ECS,\ ECS^2).$$

where Y = crack movement, in.X10^{-3}.

T = temperature, F.

ECS = Effective Crack Spacing, ft.

Also, several models of the form:

$$Y = f(T, ECS,\ ECS^2,\ GFU)$$

where GFU = geological formation unit.

were developed to analyze the effect of the geological formation underlying a cracked section of the pavement.

The SAS program was also used to conduct tests for evidence of real differences in the observed values. The results of these tests indicated the observed significance level and acceptance or rejection of the null-hypothesis (no-difference) was based on a reasonable significance level value of 0.05. Because measurements were taken from the same cracks during the study and not from randomly selected cracks each time, it was suspected that the magnitude of the experimental error would be reduced. Smaller experimental errors give smaller observed significance levels and a tendency to reject the null-hypothesis. This usually becomes critical when the observed significance level is close to the rejection level. Fortunately, the observed significance levels in this study were either very high or very low, and this problem was not encountered. The results of this analysis and the correlation studies with the three affecting factors (temperature, effective crack spacing and geological formation unit) are discussed below.

Temperature

Based on a preliminary study of the relationship between the crack movement and the recorded temperatures, the analysis of the temperature affect was made using only the subsurface pavement temperature. This study indicated that correlation with subsurface temperature was higher than with either air temperature or the pavement surface temperature. This had been expected because temperature measurements for both air and pavement surface were influenced by ambient conditions not considered, i.e., wind velocity and solar radiation. Also, there is an inherent lack of reliability in measured surface temperatures due to factors discussed by Straub (6).

Point of Curvature: Inspection of the scatter diagrams for sub-surface temperature versus movement suggested the possibility of a skewed relationship for the data obtained during the warming cycle of a given pavement section (Figure 9). The heating line appears to have an inflection point at some particular temperature. This phenomenon was reported by Littlefield (10) in his investigation of the thermal expansion behavior of asphalt concrete materials. He also found that differences in grade and source of asphalt cement yielded different temperatures for the beginning of the curved portion of the plot which he called the point of curvature (PC).

It is thought that the following factors, either separately or jointly, are responsible for this phenomenon. 1) Because asphalt is a viscoelastic material, it has the characteristics of a solid at low temperatures. At high temperature it responds as a viscous liquid and, since asphalt concrete is a mixture of asphalt cement and graded aggregate, the transition point between these two states in the mixture is not sharp. At low temperatures, the length of a sample varies linearly with temperature. At high temperature, the asphalt acts as a liquid and does not transmit the expansion forces but rather tends to flow from points of high pressure towards lower pressure areas. In doing so, it extrudes laterally and the longitudinal expansion of a sample is greatly reduced. Thus, the expansion in the longitudinal direction would be primarily due to expansion of the aggregate in the sample. Even though the absolute volume does increase with temperature, at high temperature it is accompanied by a different rate of change in length. 2) Particulate materials (sand, spawl from crack sides, etc.) partially fill the opened crack and then provide compressional resistance when the adjacent pavement sections expand and the crack begins to close. This reduces the rate of change of crack width during a warming cycle.

The PC points were determined for each site using a computer

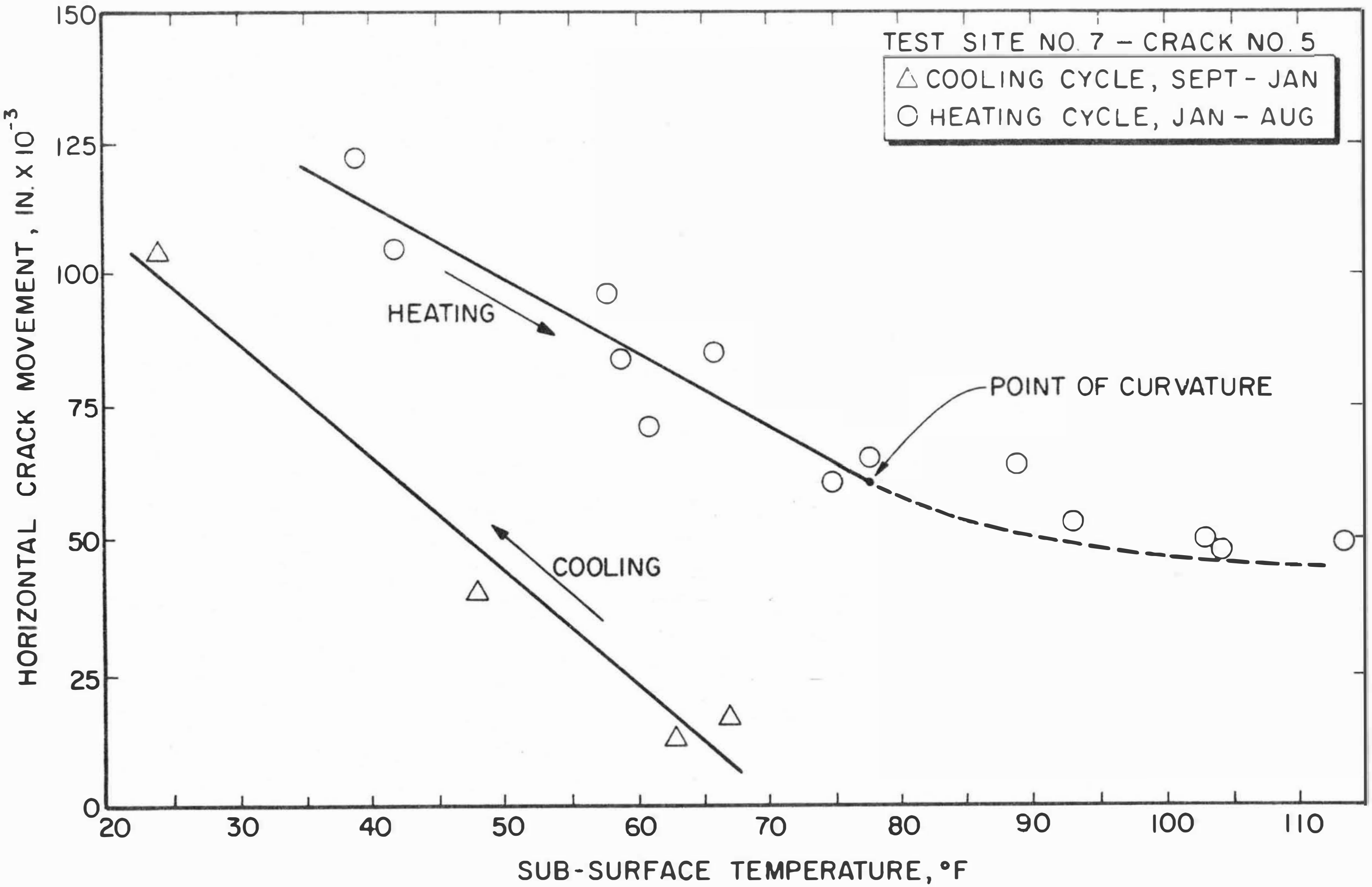


Figure 9. A Scatter Diagram for Relationship Between Horizontal Movement and Pavement Sub-Surface Temperature

program to solve equations derived by Holbert and Broemeling (11). Results were obtained in the form of a probability associated with each of the measured temperatures corresponding to the PC in a given test site. The average PC temperatures are given in Table I, which lists the points with the highest probability. Table III in Appendix A shows a summary of the computer results.

The average amount of crack movement that takes place between 0 F (-17.8 C) and the PC temperatures are shown in Table II. Approximately 80 percent of the total movement at a crack occurs between these two temperatures. This percentage of movement is very close to what Littlefield found in his study (10). This strongly implies that the temperature of the PC is closely related to the properties of the asphalt concrete material.

Only measurements associated with subsurface temperatures colder than at the PC of each site were used to fit the regression models for the study. Measurements at temperatures higher than at the PC were not included, because the movement behavior of the cracks were completely different in these two regions.

Temperature Effect: Temperature had a very significant affect on crack movement. The regression lines, coefficient of determination (R^2) and observed significance level ($\hat{\alpha}$) for the temperature affect are illustrated in Figure 10. Extrapolating the regression lines to 0 F (-17.8 C), based on Oklahoma climatic data, the average amount of opening is about 0.25 in. (6 mm).

It is interesting to note that measurements taken during the cooling period (September through January) were smaller than the ones taken at

TABLE I

TEMPERATURES AT THE POINT OF CURVATURE FOR TEST SITES

Site No.	Temperature at Point of Curvature, °F
1	63
3	88
4	88
5	74
6	75
7	78
8	67
9	79
Average	77

TABLE II

AVERAGE AMOUNT OF HORIZONTAL CRACK MOVEMENT BELOW PC TEMPERATURE

Site No.	Crack* Movement at 0°F in. $X10^{-3}$	Crack Movement at PC in. $X10^{-3}$	% Of Movement Below PC Temp.	Average %
1	143	28	80	
3	105	16	85	
4	367	0	100	
5	235	49	79	83
6	221	8	96	
7	266	23	91	
8	142	0	100	
9	198	129	35	

*Estimates based on Mathematical Model

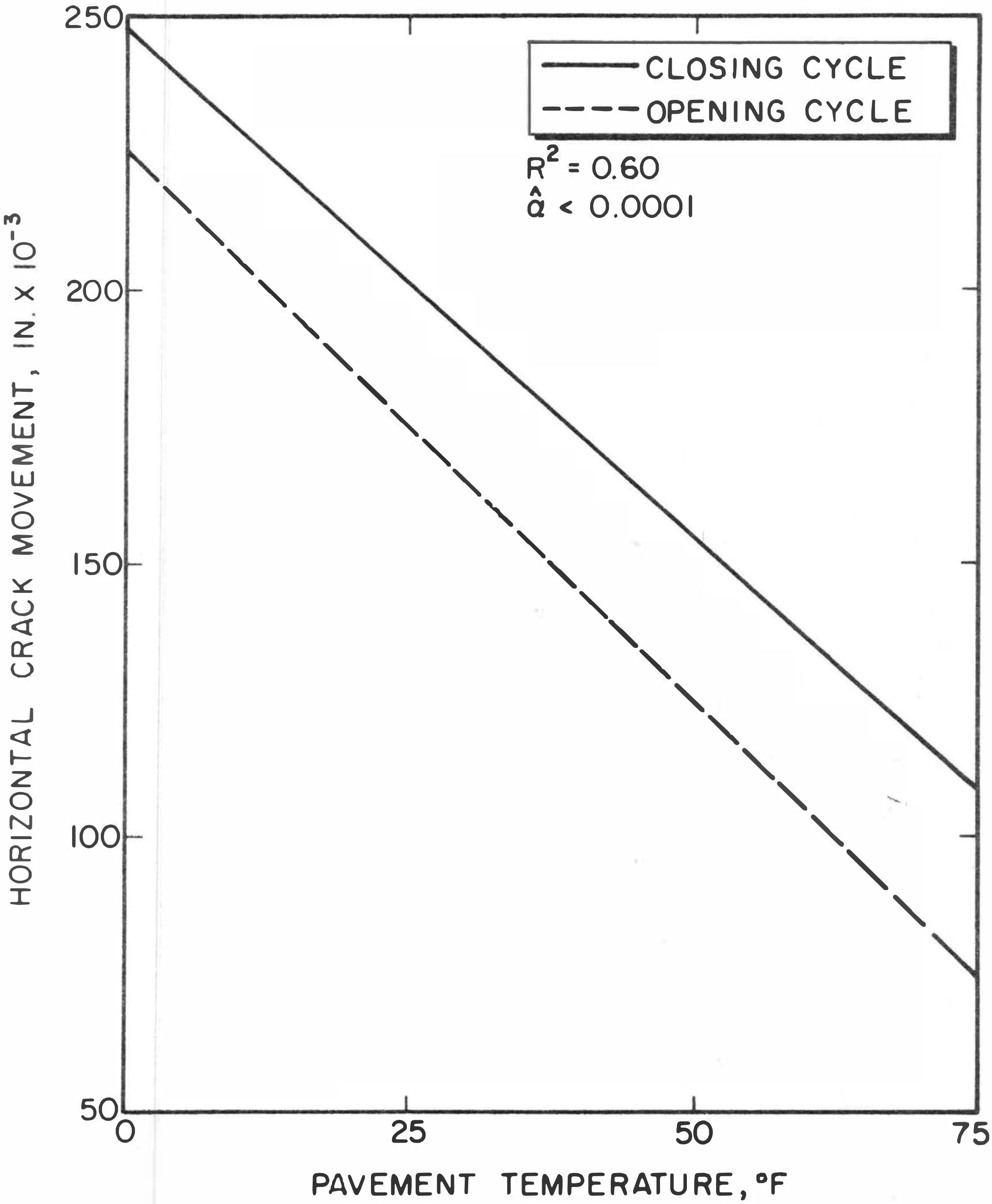


Figure 10. Relationship Between Pavement Temperature and Horizontal Crack Movement (Max. ECS=123 ft)

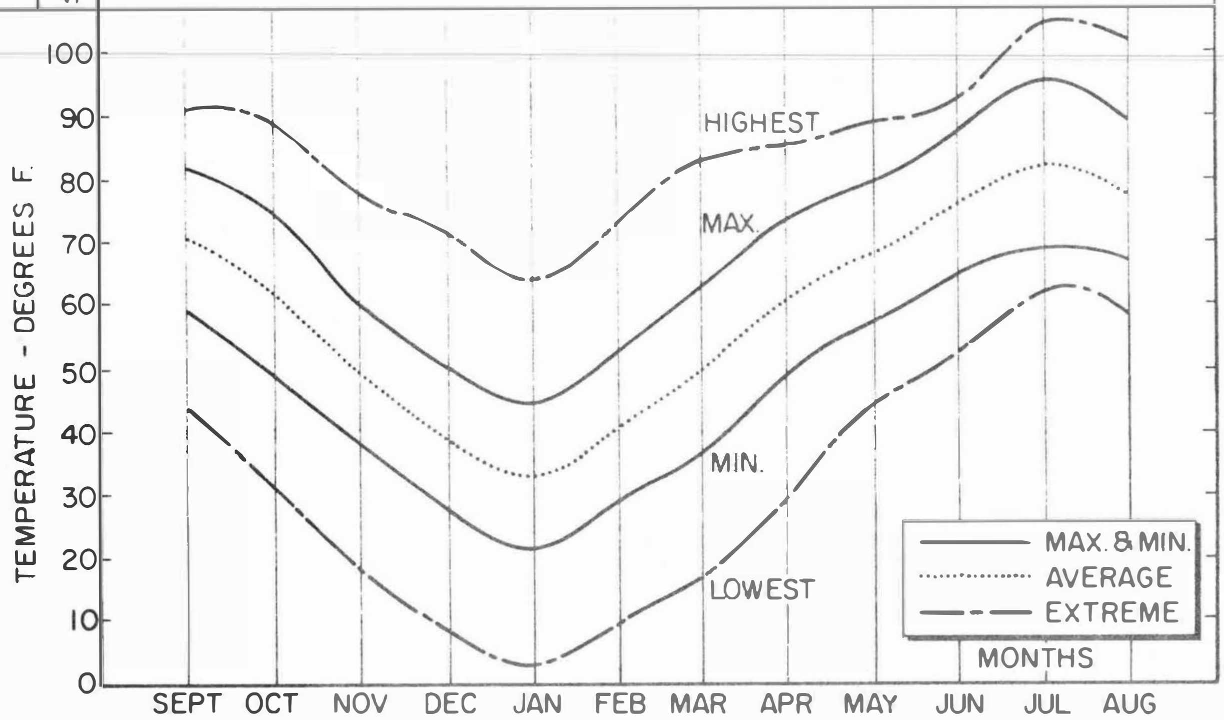
comparable temperatures during the heating period (January through August). This is illustrated in Figure 9. The existence of two lines was highly significant ($\hat{\alpha}$=0.0001). Also the lines were significantly not parallel to each other ($\hat{\alpha}$=0.03). These results indicate that the opening "potential" is greater than the closing "potential". That is, a crack will not close to its original width of opening. A permanent increment in crack width will remain after each yearly cooling and heating cycle. The average amount of the permanent opening during a one year cycle was found to be about 0.03 in. (0.8 mm).

This concept of a permanent increment of crack width helps to explain why cracks that usually start as unseen hairline cracks develop with the years into relatively wide ones. Littlefield (10) reasoned that this was the result of densification in the asphalt concrete material due to the cooling and heating cycles.

Climatic Data: Recorded temperature information (12) from stations located close to the test sites were averaged for a five year period to correlate the model temperatures with respective months of the year. Figure 11 shows that temperature changes uniformly from its highest in July to its lowest in January. This figure also indicates that minimum air temperatures experienced during January and February may be maintained long enough for the pavement to cool to 0 F (-17.8 C).

Figure 12 shows the results of applying the average monthly temperature data to the general movement model. Since the usual time for applying crack sealants is in the fall, this plot indicates that the applied sealants are subjected to almost equal amounts of extension and compression. This important fact was not taken into consideration in any of the cited laboratory bond ductility testing procedures (1).

NO. OF DAYS MAX. TEMP. °F	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
≥90	5.6	0.98	0	0	0	0	0.1	0.1	2.2	11.1	26.7	22.9
≤32	0	0	0.6	1.3	7.1	3.1	0.2	0.1	0	0	0	0



NO. OF DAYS MIN. TEMP. °F	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
≤32	0	1.4	9.7	22.2	25.6	18.6	10.3	1.5	0	0	0	0
≤0	0	0	0	0	0.7	0.2	0	0	0	0	0	0

Figure 11. Relationship Between Average Climatic Temperatures for Test Locations and Months of the Year (Average for 5 Years, 1974-1979)

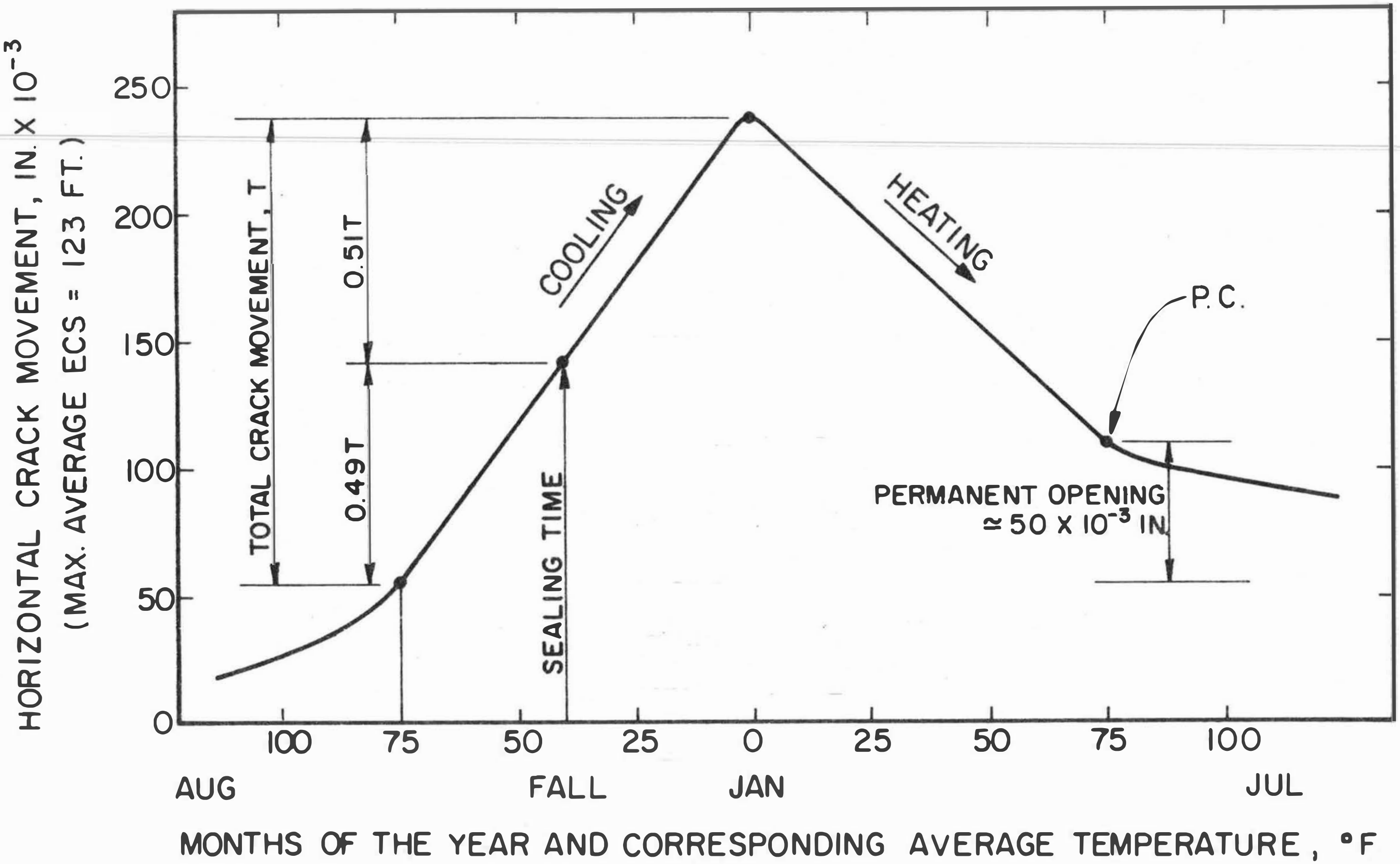


Figure 12. Relationship Between Horizontal Crack Movement and Average Seasonal Temperature

Effective Crack Spacing (ECS)

As can be seen in Figure 13, the amount of crack movement increases with increasing values of ECS ($\hat{\alpha}$=0.0001), till it reaches a peak between 100 and 125 ft (31 and 38 m) and then the movement decreases. The ECS^2 term in the model was highly significant with an observed significance level equal to 0.0001.

Since the road surface is more or less bonded to the underlying base course, these results indicate that the freedom of movement of the asphalt concrete surface is reduced by frictional forces. These frictional forces will increase as the length of paved surface increases until horizontal movement is stopped. The average amount of movement per inch of surface length per degree F was calculated for each test site and these values are presented in Table III. Comparable figures of the coefficient of thermal expansion for bond free asphalt concrete surfacing (10), were about three times higher than the tabular values. The difference is due to the developed frictional forces, which depend on the bond between surface and base as well as the stability of the base course.

The resistance to expansion movement will produce compression stresses and the resistance to shrinkage movement will produce tensile stresses in the surfacing material. In cold weather if the effective crack spacing is large, these stresses will be great enough to cause another crack at approximately the midpoint between adjacent cracks. This new crack will reduce the ECS and the tensile stresses. However, if the reduced stresses are still greater than the tensile strength of the asphalt concrete surfacing, additional midpoint cracks will develop.

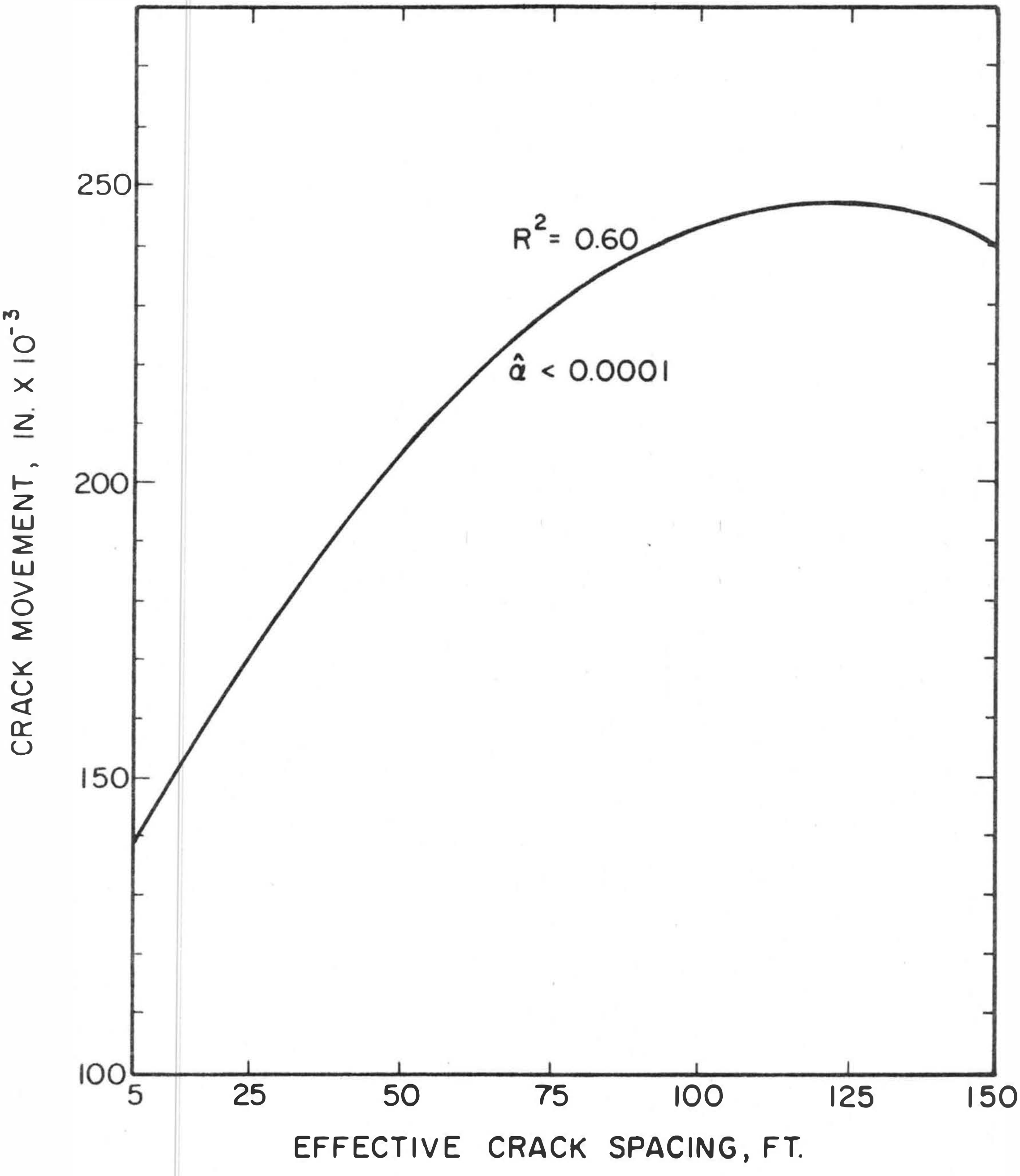


Figure 13. Relationship Between Effective Crack Spacing and Horizontal Crack Movement

TABLE III

AVERAGE HORIZONTAL CRACK MOVEMENT PER INCH OF PAVEMENT LENGTH PER DEGREE FARENHEIT

Site No.	Average ECS, ft.	Movement at 0°F, in.X10^{-3}	Average Movement/°F=in., in.X10^{-6}
1	35	143	5.206
3	40	105	2.270
4	105	367	2.496
5	63	235	3.020
6	55	221	3.889
7	81	266	2.295
8	25	142	12.470
9	40	198	2.204

Results of a correlation study to investigate the general trend of the crack movement with test site average ECS values from Table III indicated a coefficient of determination (R^2) equal to 0.89 (Figure 14). This is a very strong relationship. The amount of crack movement at 0 F was found to increase as the pavement section average ECS increased. This result emphasizes the previous discussion about the additional crack development mechanism to reduce movement stresses.

Geological Formation Unit (GFU)

The variation between the study sections or test sites was highly significant ($\hat{\alpha}<0.0001$). This variation is thought to be due to differences in one or more of the following: 1) location or climatic affect, 2) initial crack widths, 3) surface and base type and thickness, 4) construction and maintenance history, and 5) geological formations underlying the cracked sections. The influence of only the latter of these factors was investigated in this study.

Site No. 3 and four other test sites were located on the Wellington geological formation. The asphalt surface at this site was an overlay on an old section of Portland cement concrete pavement. The analysis of variance showed that this section differed significantly from other sites on the Wellington formation and also from all other sites on flexible bases ($\hat{\alpha}<0.0001$). The results of this analysis indicate that site No. 3 should not be grouped with the other Wellington sites but given a classification of its own with no regard to geological formation.

Geological formation unit terms were introduced in the model to study their effect on the behavior of the cracks. Each GFU was given a separate designation term. Test site No. 3 on the Wellington formation

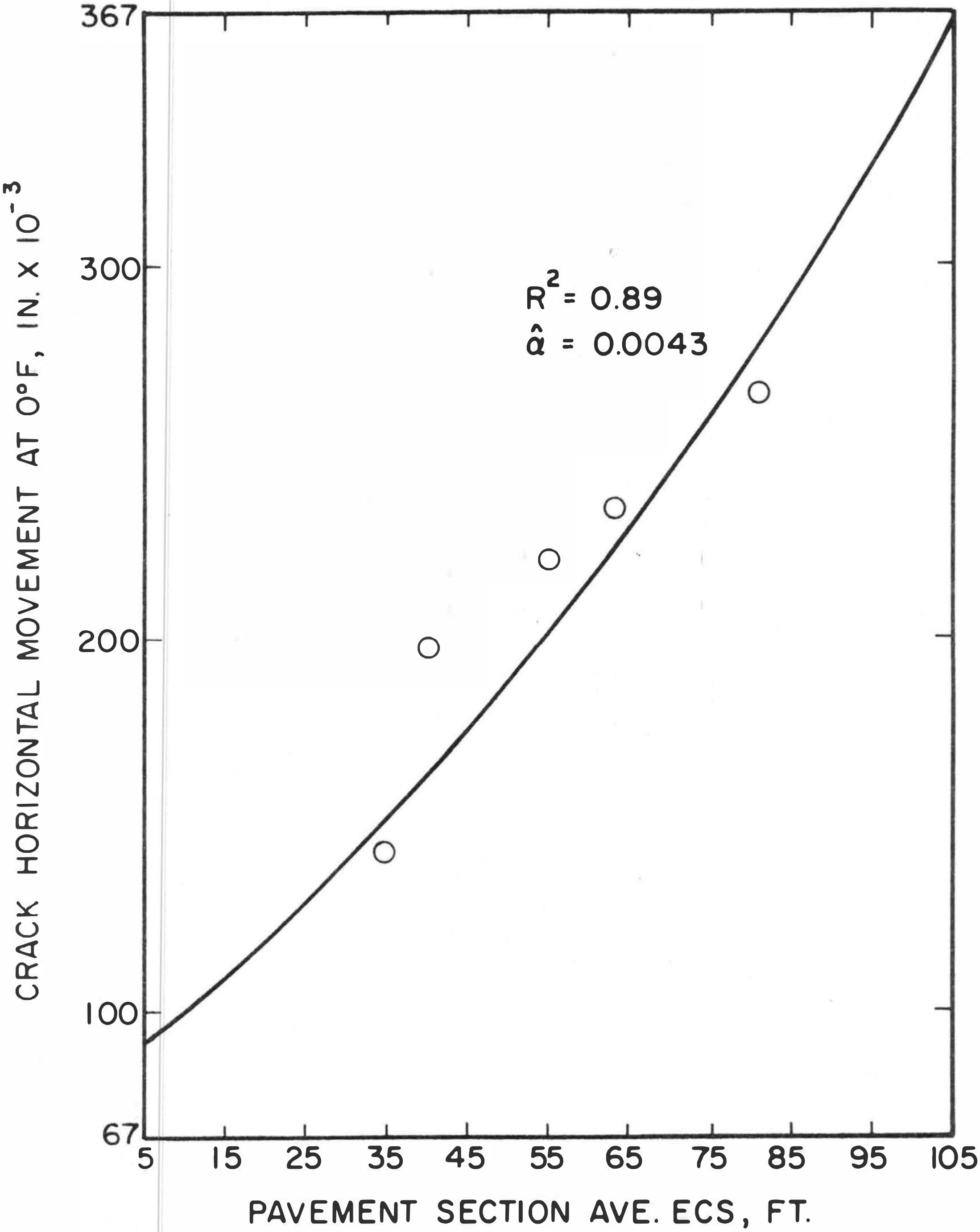


Figure 14. Relationship between Horizontal Crack Movement at 0°F and Average ECS

was assigned a designation term of its own. The observed significance level for this grouping was <0.0001.

The differences between the model describing variations among study sections and the one for geological formation units were significant ($\hat{\alpha}$<0.005). This result indicates that a great portion of the variation among the sections was unexplained by the GFU's effect. Determination of the exact amount of variation explained by the GFU is not possible from the study data. However, such a determination could be made through a comparison of the analysis of variance of several models. The results showed that adding the test site terms to the model had increased its capability to describe the data by about 34 percent above the general model. Adding the geological formation group terms increased it only 28 percent above the general model capability.

The interaction between temperature and GFU was highly significant ($\hat{\alpha}$ = 0.0001), indicating that temperature has a different effect on the behavior of cracks located on different geological formation units. The regression lines, coefficients of determination and corresponding observed significance levels ($\hat{\alpha}$) are illustrated in Figures 15 and 16 for opening and closing cycles respectively.

Average values for the slopes of these regression lines are shown in Table IV. These values are a measure of the temperature effect on crack movement, i.e., the greater the slope, the greater the amount of crack movement and, thus, greater stresses applied to a sealant material. Study site No. 4, located on the Garber formation, had the greatest slope value and was followed by the sites on the Wellington, Senora and Boone formations respectively. The regression line slope for the concrete overlay study site was on the average about three times smaller

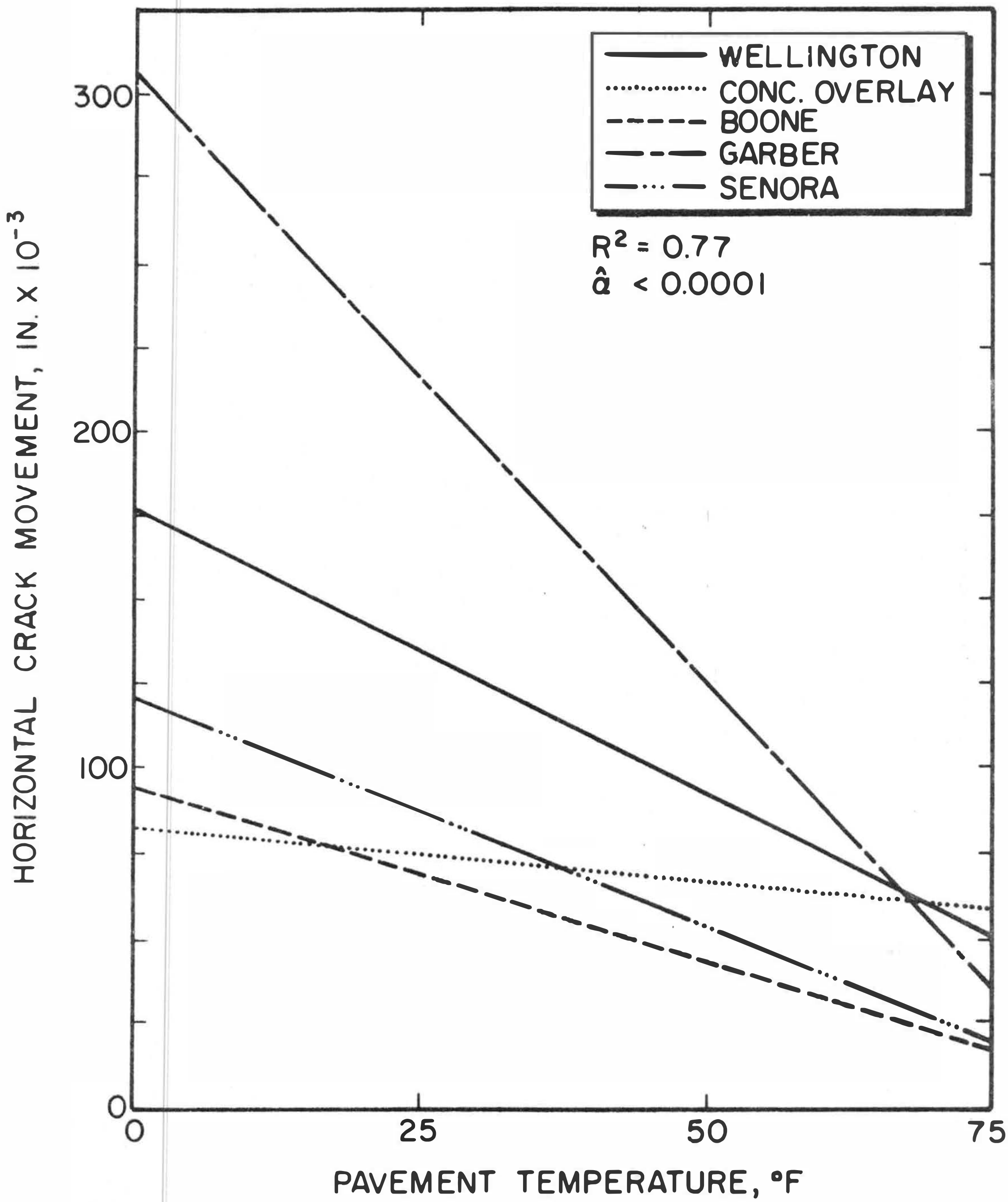


Figure 15. Relationship Between Opening Movement and Pavement Temperature (Optimum ECS Used for Each Unit)

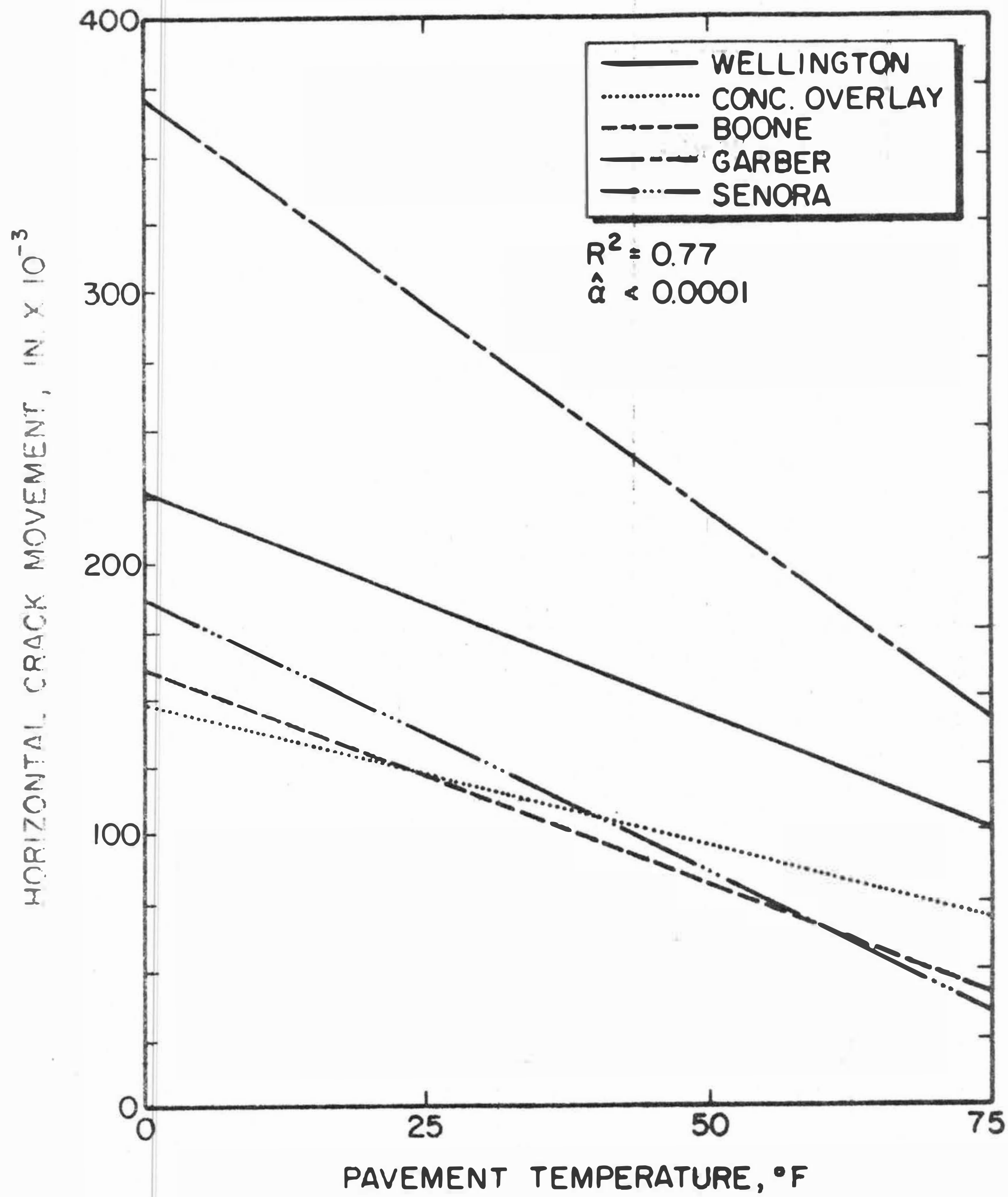


Figure 16, Relationship Between Closing Movement and Pavement Temperature (Optimum ECS Used for Each Unit)

TABLE IV

AVERAGE REGRESSION LINE SLOPE (TEMPERATURE VS MOVEMENT) FOR GEOLOGICAL FORMATION UNITS

Regression Line Slope, in.X10^{-3}/°F	Corresponding GFU
3.32	Garber
1.87	Wellington
1.67	Senora
1.22	Boone
0.7	Con. Overlay

than the rest. Since the average thermal coefficient of expansion between 0 F and 80 F (-17.8 C and 26.7 C) for bituminous concrete is about four times than that of portland cement concrete (7), this result substantiates that an underlying concrete pavement has a different and predominant effect on crack movement.

The analysis of variance indicated a high significance level for the interaction between ECS and geological formation unit ($\hat{\alpha}$ = 0.005). Figure 17 shows the ECS effect for sites located on different geological formations. The ODOT Research Division reported cracking problems with pavements located on the Boone Chert formation. Figure 17 shows that on this formation, reducing the ECS by the development of additional transverse cracks greatly reduces the amount of pavement expansion and contraction. Subgrade conditions appear to intensify the horizontal movements of the pavement and when transverse cracks develop they multiply more rapidly than on the other geological formations.

Vertical Movement

Effect of Beam Position on Measurements

In this study a Benkelman beam was used to measure the vertical movement of the crack sides. The beam probe was placed to the side of the truck's dual tires rather than in the usual between the tires position. A factorial experiment was designed to determine what difference this placement of the beam probe had on both the relative displacement and the total deflection of the cracks.

Comparable measurements were made at site No. 3 during the four season period of the study. The average vertical movement values are

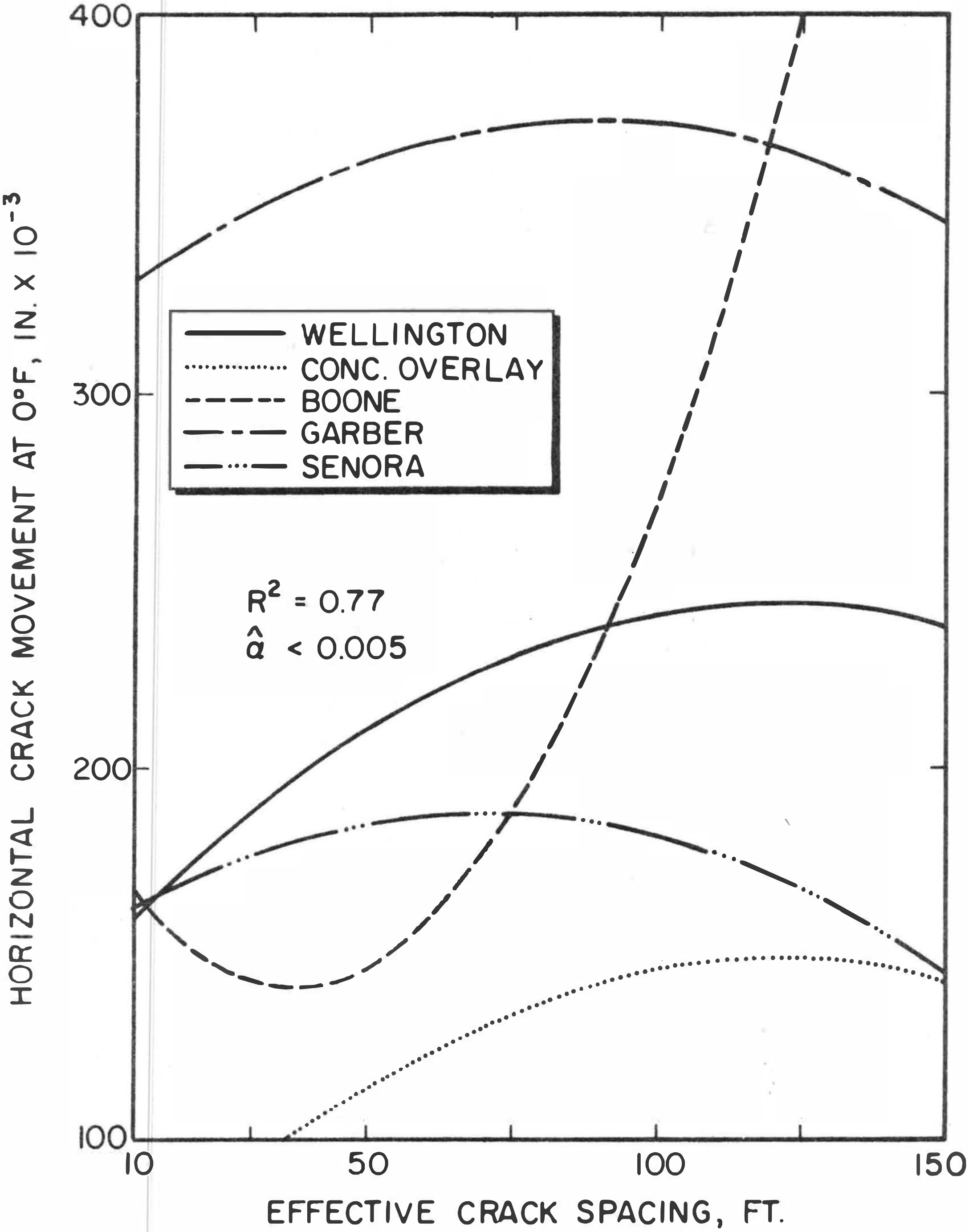


Figure 17. Relationship Between ECS and Horizontal Movement at 0°F for Cracks on Different Geological Formations for Closing Cycle

given in Table V. The analysis of variance did not show evidence of significant difference between the two measuring methods in the case of relative displacement ($\hat{\alpha}$<0.103). However, a strong evidence of difference was found in the case of total crack deflection ($\hat{\alpha}$ = 0.0001). Results of the correlation analysis are shown in Figure 18. These results indicate that the method of beam placement had little or no effect on measurements taken to determine the relative displacement of the crack sides.

Relative Displacement and Total Deflection

Deflection measurement data were analyzed by the Analysis of Variance Procedure (ANOV.PROC.) SAS computer program. Analyses were made for both relative and total deflections. The analysis of variance showed that the seasons has a significant effect on both deflection values ($\hat{\alpha}$=0.0001). Although the interaction between seasons of the year and study sites were significant ($\hat{\alpha}$=0.0001), in general, the highest deflection values were observed during the winter-spring period. Average values for relative and total deflections are given in Table VI.

A correlation study was made to investigate the relationship between the relative displacement and the total deflection. Data was fed into a Hewlett-Packard Calculator Plotter (Model 9862A) to determine the appropriate fitted curve and the coefficient of determination (R^2) was then computed by the SAS computer program. As can be seen in Figure 19, a strong relationship exists between the relative displacement and total deflection with an observed significance level $\hat{\alpha}$<0.0001.

Relative vertical displacement of opposing crack edges is a measure of the shearing strain to which a sealant would be subjected. A previous investigation (7) indicated that the effect of vertical movements on

TABLE V

AVERAGE VERTICAL DEFLECTIONS
FOR SITE NO. 3

Vertical Movement, in.X10-3	Wheel Position	SEASONS			
		Winter	Spring	Summer	Fall
Relative Displacement, D, in.X10^{-3}	Outside Wheels	17.364	2.076	0.526	10.036
	Between Duals	18.852	1.008	0.302	13.890
Total Deflection, T, in.X10^{-3}	Outside Wheels	25.250	14.000	11.600	20.650
	Between Duals	31.100	18.450	15.900	26.250

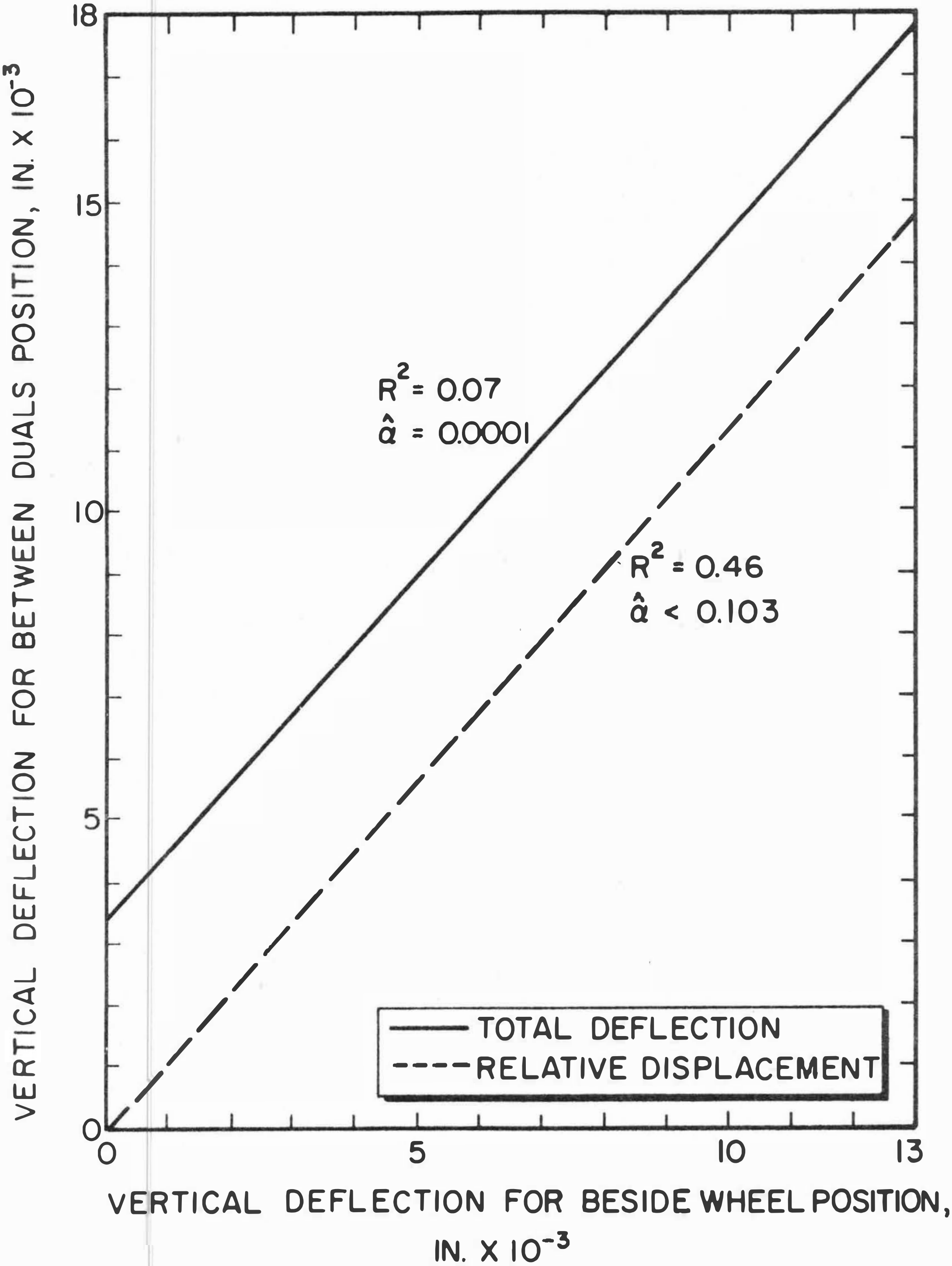


Figure 18. Relationship Between Benkelman Beam Position Measurements for Site No. 3

TABLE VI

AVERAGE RELATIVE DISPLACEMENTS AND TOTAL DEFLECTIONS AT THE STUDY SITES

Season	Site No.	Relative Displacement, in.X10^{-3}		Total Deflection, in.X10^{-3}	
		Site Avg.	Season Avg.	Site Avg.	Season Avg.
Winter	1	15.588	15.353	24.040	22.184
	3	17.364		25.250	
	4	20.750		28.500	
	5	14.728		18.600	
	6	15.900		20.900	
	7	9.902		16.800	
	8	13.424		21.200	
Spring	1	11.464	13.837	18.550	23.999
	3	2.076		14.000	
	4	17.288		27.550	
	5	10.750		18.100	
	6	15.938		28.050	
	7	14.600		28.800	
	8	24.740		32.942	
Summer	1	7.350	11.419	11.700	20.736
	3	0.526		11.600	
	4	15.426		21.550	
	5	8.276		15.400	
	6	13.100		24.400	
	7	14.638		28.550	
	8	20.614		31.950	
Fall	1	9.400	10.533	15.000	20.000
	3	10.036		20.650	
	4	11.514		21.650	
	5	10.202		17.700	
	6	10.962		20.050	
	7	8.690		20.850	
	8	12.926		24.100	

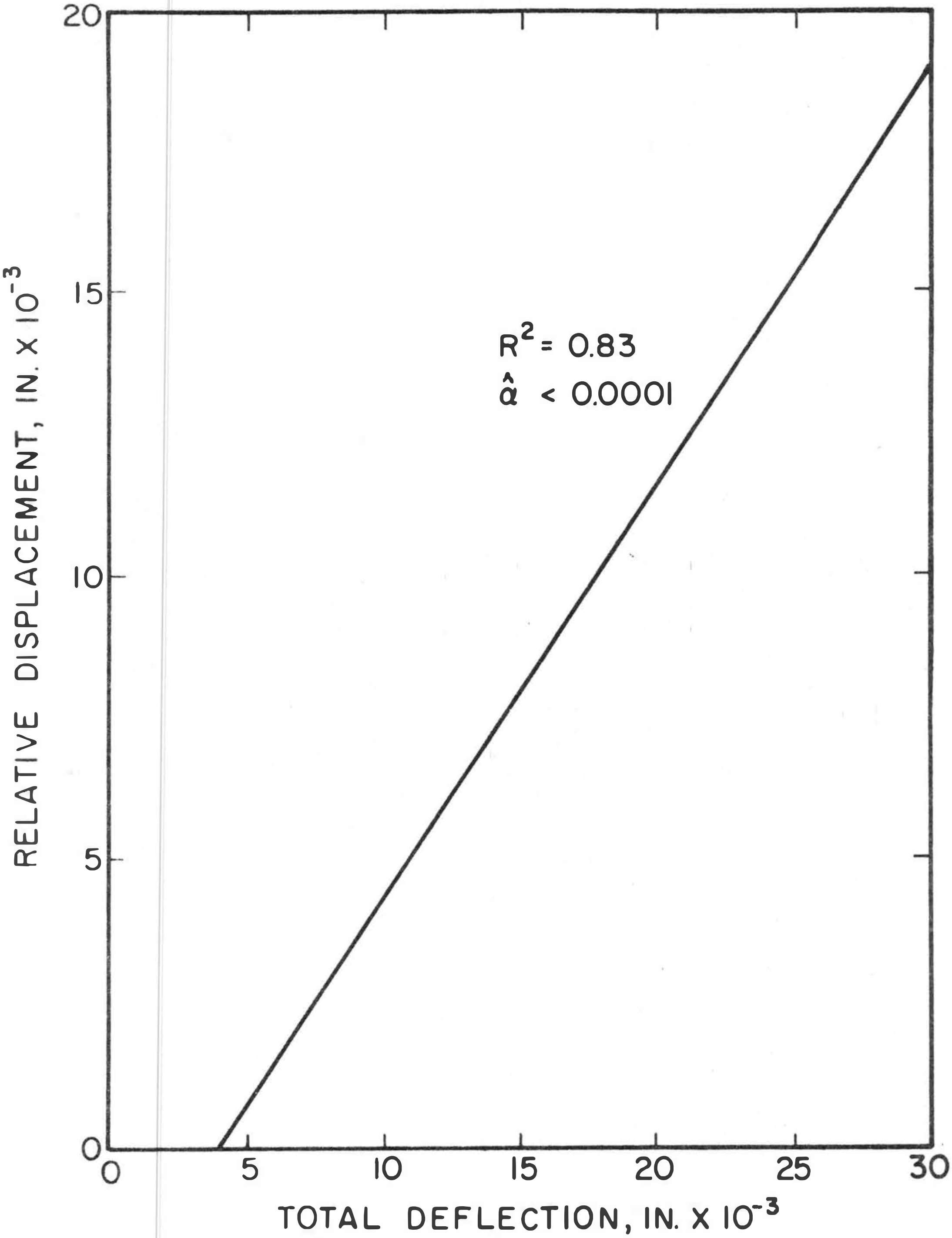


Figure 19. Relationship Between Total Deflection and Relative Displacement

joint sealers was negligible in comparison to the effect of horizontal movements.

In order to check this finding, an estimate of the horizontal crack movement that might be expected during the four seasons of a year was calculated using the regression model and a five year average temperature (5) for the respective seasons. The computed horizontal crack opening values were compared with the measured relative vertical displacements at each test site for the corresponding season (Table VII). On the average, the vertical or shear strain was 10.4 percent of the horizontal or tensile strain. As expected, this percentage value was about double that obtained in the study of portland cement concrete expansion joints (7). However, the shear strain is still small enough to not be considered a major factor in sealant failure.

TABLE VII

AVERAGE RATIO OF RELATIVE VERTICAL DISPLACEMENT TO HORIZONTAL CRACK OPENING

Site No.	Ratio of Relative Vertical Displacement to Horizontal Crack Opening*			
	Season	Site-Season Average Ratio	Study Site Average, %	Average, %
1	Winter	.104	9.60	10.4
	Spring	.116		
	Summer	.097		
	Fall	.067		
2	Winter	.180	8.6	
	Spring	.037		
	Summer	.013		
	Fall	.115		
4	Winter	.059	6.2	
	Spring	.073		
	Summer	.079		
	Fall	.035		
5	Winter	.068	6.7	
	Spring	.075		
	Summer	.075		
	Fall	.051		
6	Winter	.078	10.3	
	Spring	.126		
	Summer	.147		
	Fall	.059		
7	Winter	.036	5.9	
	Spring	.075		
	Summer	.089		
	Fall	.035		
8	Winter	.088	25.3	
	Spring	.323		
	Summer	.504		
	Fall	.096		

*Estimates for horizontal crack opening calculated using regression model and average 5 yrs. seasonal temperature.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the information compiled during the study of transversely cracked flexible pavement sections on Oklahoma highways, the following conclusions are made:

1. Under typical Oklahoma climatic conditions, the average maximum amount of horizontal crack movement observed at the test sites was 0.25 in. (6 mm).

2. About 80 percent of the total horizontal crack movement occurred between subsurface pavement temperatures of 0 F and 77 F (-17.8 C and 25.0 C).

3. The relationship between horizontal crack movement and subsurface pavement temperature differs considerably during the annual heating and cooling periods experienced by the pavement.

4. A permanent incremental increase in crack width remains after each yearly cooling and heating cycle. For the cracks studied, the average increase in crack opening was 0.03 in. (0.8 mm) per year.

5. Sealants applied during the fall season are subjected to about equal amounts of extension and compression following their installation.

6. The amount of horizontal crack movement increases with increasing values of ECS up to approximately 120 ft (37 m). Frictional resistance to this movement during cooling of the pavement produces tensile

stresses that can cause additional cracks at the mid-point between adjacent transverse cracks.

7. The geological formation on which a pavement is constructed does have an effect on subsequent cracking of the pavement and crack behavior but this relationship could not be exactly determined. The greatest amount of crack movement was observed at test sites on the Garber formation and there was indication of a high cracking potential in pavements on the Boone Chert formation.

8. The largest vertical deflections at transverse cracks were observed during the winter and spring seasons.

9. The relative vertical displacement of the crack sides, under an 18,000 lb (8,165 kg) axle load, was approximately 10 percent of the horizontal crack movement.

Recommendations

From the results and the observations of this study, the following recommendations are made:

1. Additional crack dynamics research should be conducted to determine the influences of: a) initial crack width, b) type and thickness of surfacing material, c) type and thickness of base material and d) underlying geological formation on horizontal crack movements.

2. Relative to the above recommendation, detailed field measurements of crack movements at temperatures below 20 F (-6.7 C) should be made to study the hysteresis in crack movement.

3. Modifications in the "Bond-Ductility" laboratory test procedure (see Interim Report III) to include both extension and compression cycles should be considered.

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APPENDIX A

TEST SITE INFORMATION

TABLE I

TEST SITE INFORMATION

Test Site Number	Highway Number	Location	Geological Formation Unit	Maintenance Division Number
1	S.H. 20	1.0 mile West of Spavinaw Dam	Boone Chert	8
2	S.H. 20	12.6 miles East of I 44 Jct.	Boone Chert	8
3	S.H. 15	2.0 miles West of I 35 Jct.	Wellington-Admire	4
4	U.S. 64	1.5 miles West of S.H. 74 Jct.	Garber	4
5	U.S. 177	0.7 miles South of U.S. 66 Jct.	Wellington-Admire	4
6	U.S. 177	4.5 miles South of U.S. 66 Jct.	Wellington-Admire	4
7	S.H. 51	0.4 miles West of S.H. 18 Jct.	Wellington-Admire	4
8	U.S. 75	4.0 miles North of Hughes County South Line	Senora	3
9	U.S. 177	1.0 mile North of U.S. 62 Jct.	Wellington-Admire	4

TABLE II

TENTATIVE SCHEDULE FOR VERTICAL CRACK MOVEMENT FIELD STUDY

Test Site No.	Main-tenance Divis. No.	Site Description	SUGGESTED DATE Winter Feb.	Spring May	Summer Aug.	Fall Nov.
1 2	8	S.H. 20, 1.0 mi W. of Spavinaw Dam S.H. 20, 12.6 mi E. of I 44 Jct.	Feb. 6, 1978 1:00 P.M. at Site No. 1	May 10, 1978 1:00 P.M. at Site No. 1	Aug. 14, 1978 1:00 P.M. at Site No. 1	Nov 14, 1978 1:00 P.M. at Site No. 1
3 4	4	S.H. 15, 2.0 mi W. of I 35 Jct. U.S. 64, 1.5 mi W. of S.H. 74 Jct.	Feb. 13, 1978 2:00 P.M. at Site No. 3	June 9, 1978 9:00 A.M. at Site No. 3	Aug. 15, 1978 9:00 A.M. at Site No. 3	Nov. 15, 1978 9:00 A.M. at Site No. 3
5 6 7	4	U.S. 177, 0.7 mi S. of U.S. 66 Jct. U.S. 177, 4.5 mi S. of U.S. 66 Jct. S.H. 51, 0.4 mi W. of S.H. 18 Jct.	Feb. 15, 1978 1:30 P.M. at Site No. 7	June 9, 1978 After Sites 3 & 4 1:30 P.M. at Site No. 7	Aug. 15, 1978 After Sites 3 & 4	Nov. 15, 1978 After Sites 3 & 4
8	3	U.S. 75, 4.0 mi N. of Hughes County south line.	Feb. 14, 1978 1:00 P.M.	May 12, 1978 1:00 P.M.	Aug. 16, 1978 1:00 P.M.	Nov. 16, 1978 1:00 P.M.

TABLE III

COMPUTER RESULTS FOR POINT OF CURVATURE TEMPERATURE PROBABILITIES

Test Site No.													
1	Temp., °F	39	43	59	63	68	75	76	100	118	122		
	Prob., %		31	23	34	9.8	.33	.36	0	0	0		
3	Temp., °F	25	38	40	50	50	76	80	81	88	94	100	121
	Prob., %	—	0	.01	.06	3.6	3.6	3.8	32.6	38.7	17.1	0	0
4	Temp., °F	28	29	58	82	88	92	98	110	123			
	Prob., %	—	.56	.58	2.2	69.1	17.9	9.6	0	0			
5	Temp., °F	24	39	58	62	74	87	94	98	103	108	110	115
	Prob., %	—	14.9	7.9	33.1	37.7	4.4	.58	.30	.48	.56	0	0
6	Temp., °F	26	39	60	65	75	87	89	95	98	105	107	109
	Prob., %	—	23.2	10.1	5.9	10.5	3.9	5.6	20.1	6.4	14.3	0	0
7	Temp., °F	39	42	58	59	61	66	75	78	89	103	104	129
	Prob., %	—	4.6	2.2	5.3	3.6	26.4	18.1	35.8	2.1	1.87	0	0
8	Temp., °F	51	67	77	85	86	98	104	107	115	124		
	Prob., %	—	67.1	31.6	.84	.41	0	0	0	0	0		
9	Temp., °F	35	40	45	46	71	79	86	98	100	100	113	114
	Prob., %	—	5.9	3.5	8.6	8.9	22.4	20.1	12.7	3.5	14.4	0	0